

On near-infrared $H\alpha$ searches for high-redshift galaxies [★]

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ABSTRACT

The lack of success of $Ly\alpha$ searches for high-redshift $z > 2$ field galaxies may be due to extinction by dust, suggesting that surveys based on lines of longer wavelength, particularly $H\alpha$, may be more effective. To test the dust hypothesis we have undertaken deep broad- (K') and narrow-band (5000 km s^{−1}, $\lambda = 2.177 \mu\text{m}$) imaging of the field towards the quasar PHL957, in an attempt to detect $H\alpha$ emission from a known galaxy of redshift $z = 2.313$. We cover an area of 4.9 arcmin² (0.28 h^{-2} Mpc²) to a 4σ limiting narrow-band flux $f = 2.7 \times 10^{-16}$ erg cm^{−2} s^{−1}, a factor of several deeper than previously published surveys. We detect the $H\alpha + [\text{N II}]$ emission line in this galaxy at the 3.3σ level, inferring a star formation rate of $18 h^{-2} M_{\odot} \text{yr}^{-1}$. This is a factor only a few times larger than the rate seen in some Sc galaxies today. The faint flux level reached in this work demonstrates the promise of narrow-band imaging in the near-infrared as a technique for finding normal galaxies at high redshifts.

Key words: galaxies: formation – quasars: absorption lines – quasars: individual: PHL957

1 INTRODUCTION

Blank-sky searches for high-redshift field galaxies ($z > 2$) through the detection of the $Ly\alpha$ emission line (de Propris et al. 1993; Thompson et al. 1993) have so far had no success. These surveys span the redshift range $2 < z < 5$, where galaxies may be experiencing their peak star formation rate (SFR), and now cover sufficiently large areas and reach such faint flux limits that they are in conflict with some theories (Djorgovski, Thompson & Smith 1993). Two competing explanations for the lack of success are (i) galaxies formed at higher redshift still (but note the unsuccessful search of Parkes, Collins & Joseph 1994), or (ii) the $Ly\alpha$ emission is severely attenuated due to extinction by dust, possibly exacerbated by resonant scattering from H I (Charlot & Fall 1991; Valls-Gabaud 1993). Surveys based on the detection of lines at longer wavelengths, especially $[\text{O II}] \lambda 3727$, $\text{H}\beta \lambda 4861$, $[\text{O III}] \lambda 5007$, and $\text{H}\alpha \lambda 6563$, benefit from greatly reduced extinction, allowing a test of the dust extinction hypothesis. The $H\alpha$ line, which lies in the K -band at redshifts $2.08 < z < 2.66$, is particularly useful because it provides a direct estimate of the SFR (Kennicutt 1993).

Thompson, Djorgovski & Beckwith (1994) have undertaken a pilot project for a near-infrared narrow-band imaging survey. They used a bandwidth of 4000 km s^{−1},

and their deepest fields reach 4σ detection limits in the range $1 - 3 \times 10^{-15}$ erg cm^{−2} s^{−1}, over a total area of 0.3 arcmin². Here we report the results of a similar pilot project, using a filter of width 5000 km s^{−1}, which reaches much greater depth, 2.7×10^{-16} erg cm^{−2} s^{−1} (4σ), and covers a considerably larger area, 4.9 arcmin². We have targeted the field of the quasar PHL957 (RA 1^h00^m33.4^s, Dec. = 13°00′11″, 1950.0), $z_{\text{em}} = 2.681$. Our aim was to detect $H\alpha$ emission from the known high-redshift galaxy in this field, $z_{\text{em}} = 2.313$, hereafter referred to as C1, which was found by Lowenthal et al. (1991). This galaxy lies at the same redshift as a damped $Ly\alpha$ absorption line seen in the spectrum of the quasar, and in fact was discovered in a narrow-band $Ly\alpha$ search for companions of damped systems. This field therefore is particularly interesting as it may contain other detectable companions of these two objects.

2 OBSERVATIONS

Our broad- and narrow-band images of the field were obtained with the IRAC2B instrument on the 2.2-m telescope at the European Southern Observatory, over the three nights from 1993 October 31 to November 2. Conditions were photometric, and the seeing ranged between 0.7 and 1.2 arcsec. The detector for IRAC2B is a NICMOS3 256² array. The pixel scale of 0.52 arcsec pixel^{−1} undersampled the seeing in the best conditions, but gave a large field of view, corre-

[★] Based on observations collected at the European Southern Observatory, La Silla, Chile

sponding to $0.5 h^{-1} \text{ Mpc}^\dagger$ comoving at the redshift of the galaxy C1.

The narrow-band filter used, ESO NB9, has a FWHM $\Delta\lambda_{\text{na}} = 0.038 \mu\text{m}$, and a central wavelength $\lambda_{\text{eff}} = 2.177 \mu\text{m}$, which closely matches the wavelength of $\text{H}\alpha$ for the galaxy. We used the ESO K' filter for the broad-band observations. This filter is slightly narrower, $\Delta\lambda_{\text{br}} = 0.32 \mu\text{m}$, than the standard K filter, and shifted to a shorter wavelength, $\lambda_{\text{eff}} = 2.15 \mu\text{m}$, thereby reducing the sky/telescope thermal background by some $0.5 \text{ mag arcsec}^{-2}$. The observations comprised several sequences of duration 45 min, each made up of 9 individual 300-s frames, performed in a 3×3 grid pattern of step size 10 arcsec. Each 300-s frame was made up of a number of co-added exposures. The integration times of the individual exposures were 50 or 100-s for the narrow-band, and 10-s for the broad-band, and were chosen such that the sky counts ensured the observations were background limited, while staying well below the saturation count level. Total integration times were 405 min for the narrow-band, and 180 min for the broad-band. The average sky brightness was $m_{\text{na}} = 12.7$, $m_{\text{br}} = 13.1 \text{ mag arcsec}^{-2}$.

From observations of standard stars we computed extinction and colour terms for both filters. All magnitudes quoted in this paper are in the natural system of the filters, zero-pointed to K , i.e. for a star of zero colour ($J - K = 0$) $m_{\text{na}} = m_{\text{br}} = K$. For the colour range of the standards used, $0.0 < J - K < 0.4$, the following equations apply:

$$m_{\text{na}} = K + 0.07(J - K), \quad (1)$$

$$m_{\text{br}} = K + 0.13(J - K). \quad (2)$$

3 DATA REDUCTION

A dark frame of the appropriate integration time was subtracted from each data frame. The subsequent stages in the data reduction are division by flat field, and sky subtraction. The number of detected photons in an individual pixel is a sum of contributions from objects (O), the sky (S), and a thermal background (T) from the telescope and instrument. Before deciding on a method of data reduction it is important to investigate the nature of the spatial and temporal variations of S and T . To do this we first formed dome flats by creating normalized frames from the difference of exposures of the dome spot with and without illumination by a flat-field lamp. Since T is present in both frames it is removed in the subtraction, and the flat field created in this way should be about as good as a dome flat at optical wavelengths, i.e. an accuracy of a few per cent on large scales, and better on small scales. For large scales this was confirmed by an analysis of frames containing standard stars placed at different positions within the frame. The counts of the stars in the flattened frames show an rms variation of 2-3 per cent.

The data frames divided by dome flats show strong gradients across each frame, of magnitude typically 25 per cent of the mean count in the frame, which may be imputed to the

thermal background. A comparison of frames taken at different times in the night shows that this background varies little with time, or with mean count level. For example the difference of two flattened frames taken 55 min apart, during which time the mean count level varied by 15 per cent, shows an rms variation of 0.3 per cent of the original mean count level. (This also provides an estimate the accuracy of the dome flat, i.e. better than 0.3/15 or 2 per cent.) We conclude that the background in our frames is characterized by two terms: (i) the night sky, which to first order is spatially flat, but temporally variable, at the level of a few per cent from frame to frame, and 20 per cent over the night, and (ii) the thermal radiation from the telescope and instrument, which to first order is temporally constant, but spatially variable, at the level of 25 per cent across the frame, and 1 per cent on the scale of a few pixels. There are additional contributions to the background, at the level of a few tenths of a per cent, in the form of arc-shaped and v-shaped patterns whose origin is unknown. These patterns are particularly pernicious because they exhibit both spatial and temporal variations. Fortunately, however, they vary smoothly both in position, on the scale of a few pixels, and in time, on the scale of a few frames.

It is common practice to use the frames themselves to flat-field infrared data. Since our data contain large gradients, this procedure would introduce systematic photometric errors equal to the magnitude of the gradients. Indeed, this was confirmed by an analysis of frames containing standard stars, flattened using data frames. The scatter in the standard-star photometry was considerably larger than that achieved with dome flats. For this reason we used dome flats for first-order flat fielding. Because the dome flats are accurate to a few per cent, which is the desired accuracy of the final photometry, it is irrelevant in practice whether the subsequent refinements to produce a flat sky background in each frame involve only subtraction, as pursued here, or a combination of division and subtraction, i.e. first obtaining a perfect flat field, followed by sky subtraction.

The sky, thermal, and pattern contributions were removed from each flat-fielded data frame in three stages. First the large-scale background was removed by subtracting a heavily median-filtered version (35×35 box) of the frame itself. The frames were then stacked, and the median of the stack was subtracted from each frame. This operation removes the average of the flat-field residuals as well as small-scale variations in the thermal background, due, for example, to dust on the dewar window. Finally a filtered version of the data cube was subtracted, using a $5 \times 5 \times 5$ box. This process removes the patterns, as well as any remaining background (thermal, or flat-field residuals) that varies slowly with time. The dimensions of the filter were the subject of experimentation to optimize the final results, as quantified by the noise in the final combined frames, as well as the agreement of the photometry between images obtained on different nights. We found that a cubic box produced better results than a one-dimensional box (e.g. $1 \times 1 \times 9$). This is because the x, y dimensions are similar to the scale of the patterns, and (presumably) because the ratio of the dome flat and the true flat field is smooth over these scales. Roughly speaking, the accuracy of the flat-field and sky subtraction processing is the product of the small-scale accuracy of the dome flat (~ 1 per cent per pixel) and the

[†] We assume a cosmology with $h = H_0/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and $q_0 = 0.5$ unless otherwise stated.

short-term variability of the sky level relative to the long-term trend (~ 2 per cent). This product (~ 0.02 per cent per pixel) is smaller than the Poisson error for a single frame (e.g. ~ 0.1 per cent per pixel for K').

A second approach to the flat-fielding and sky subtraction used regression fits to the data, and solved, in an iterative manner, for the three functions, *vis* the flat field $F(x, y)$, the thermal contribution $T(x, y)$, and the sky level $S(t)$. This approach produced very similar results.

The reduced frames were registered, scaled (to account for variations in the airmass), and then co-added, weighting by the inverse of the scaled sky variance, while using a percentage clipping algorithm to remove any discrepant data points, due for example to cosmic-ray strikes. Bad pixels flagged in a mask frame (1 per cent of all pixels) were ignored in the co-addition.

The dithering employed means that the edge regions of the mosaicked final images have a greater noise level, since fewer data frames contribute than in the central region of common overlap. Therefore we trimmed the mosaicked images to the central 256×256 pixel region. The noise in the sky is uniform over most of this region, but rises slightly towards the edges. The final broad- and narrow-band images are shown in Fig. 1.

4 RESULTS

To search for candidate high-redshift galaxies we performed aperture photometry, with a radius $r = 3$ pixels (1.56 arcsec), on all objects visible in the narrow-band frame, and selected the 30 objects detected at signal-to-noise ratio > 4 for subsequent photometry in the broad-band frame. The measured magnitudes were converted to approximate total magnitudes using an aperture correction measured from the brightest objects. It is convenient to scale the frames to the same zero-point, such that the relation between total apparent magnitude m and counts within the aperture C , for both frames, is given by

$$m = 25 - 2.5 \log_{10} C. \quad (3)$$

The measured noise in the sky in the central regions of the scaled frames is then $\sigma_{\text{na}} = 8.60$ counts pixel $^{-1}$, and $\sigma_{\text{br}} = 3.95$ counts pixel $^{-1}$, which is close to the Poisson limit, and corresponds to $m_{\text{na}} = 22.0$ mag arcsec $^{-2}$ and $m_{\text{br}} = 22.8$ mag arcsec $^{-2}$. The 4σ detection limit is $m_{\text{na}} = 19.3$, or a narrow-band flux $f = 2.7 \times 10^{-16}$ erg cm $^{-2}$ s $^{-1}$.

The results of the photometry are shown in Fig. 2 which plots the $m_{\text{br}} - m_{\text{na}}$ colour versus narrow-band magnitude m_{na} . The typical colour of objects in this plot is $m_{\text{br}} - m_{\text{na}} \sim 0.1$. This suggests that most of the objects are of rather late stellar spectral type, for example cool stars, or elliptical galaxies. Objects in the redshift range $2.29 < z < 2.35$ with strong $\text{H}\alpha + [\text{N II}]$ emission lines will lie above the sequence of normal objects. The galaxy C1 itself lies at the top of Fig. 2. The measured magnitudes and colour for this galaxy are provided in Table 1. The object is detected at 4.5σ in the narrow-band, but is very faint in the broad-band (1.9σ).

To select candidate high-redshift galaxies we quantify the significance of the excess flux in the narrow-band by computing a parameter Σ , which is the number of standard deviations between the counts measured in the broad-band

Table 1. Properties of galaxy C1.

| | |
|---|--|
| Offset rel. to PHL957 * | 42.6''W, 24.1''N |
| m_{na} | 19.22(4.5 σ) |
| m_{br} | 20.99(1.9 σ) |
| $m_{\text{br}} - m_{\text{na}}$ | 1.77 |
| Colour significance Σ | 3.3 |
| $EW_{\text{rf}} \text{H}\alpha + [\text{N II}]$ | $> 220 \text{ \AA}$ (2σ) |
| $f_{\text{H}\alpha}$ | $2.1 \pm 0.6 \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}$ |
| SFR $q_0 = 0.1$ | $36 \pm 10 h^{-2} \text{ M}_{\odot} \text{ yr}^{-1}$ |
| SFR $q_0 = 0.5$ | $18 \pm 5 h^{-2} \text{ M}_{\odot} \text{ yr}^{-1}$ |

* Offsets computed assuming the frame is oriented N – S. The measured position angle in our frames of star A (Fig. 1) relative to PHL957 is 187.9° .

and the number expected on the basis of the narrow-band counts. Where an object is extremely faint in the broad-band, the error-parameter Σ is well-defined even in cases where the integrated counts within the registered aperture are negative, and m_{br} is undefined. In computing Σ we assume that only the noise in the sky contributes to the errors. For simplicity we suppose zero colour $m_{\text{br}} = m_{\text{na}}$, which may be approximately correct for the continuum of a high-redshift galaxy. Lines of constant Σ are plotted in Fig. 2. The relation between measured colour and Σ is given by

$$m_{\text{br}} - m_{\text{na}} = -2.5 \log_{10} [1 - \Sigma 10^{-0.4(25 - m_{\text{na}})} \sqrt{\pi r^2 (\sigma_{\text{na}}^2 + \sigma_{\text{br}}^2)}] \quad (4)$$

where r is the aperture radius, 3 pixels.

Because of the small photometric errors at bright magnitudes, objects with only a small colour excess (either because they are red, or because they have lines of small equivalent width) have large values of Σ . Therefore we need to impose an additional criterion of a minimum equivalent width for the $\text{H}\alpha + [\text{N II}]$ line. Lines of constant rest-frame equivalent width EW_{rf} are plotted in Fig. 2, computed from the relation

$$EW_{\text{rf}} = \frac{\Delta\lambda_{\text{br}} \Delta\lambda_{\text{na}} [1 - 10^{-0.4(m_{\text{br}} - m_{\text{na}})}]}{[\Delta\lambda_{\text{br}} 10^{-0.4(m_{\text{br}} - m_{\text{na}})} - \Delta\lambda_{\text{na}}] (1 + z)} \quad (5)$$

For C1 we measure $\Sigma = 3.3$, and $EW_{\text{rf}} = 1190 \text{ \AA}$, with a 2σ lower limit $EW_{\text{rf}} > 220 \text{ \AA}$, confirming that we have detected the $\text{H}\alpha + [\text{N II}]$ line from this galaxy. The measured $\text{H}\alpha$ line flux and estimated SFR are provided in Table 1. The $\text{H}\alpha$ line flux is calculated from the relation

$$f_{\text{H}\alpha} = \frac{\Delta\lambda_{\text{br}} [1 - 10^{-0.4(m_{\text{br}} - m_{\text{na}})}]}{(\Delta\lambda_{\text{br}} - \Delta\lambda_{\text{na}})} \frac{10^{-0.4(m_{\text{na}} + 19.57)}}{1.33} \quad (6)$$

where the first term corrects for the contribution of the continuum to the narrow-band flux, and the second term converts from magnitude to flux and corrects for the contribution of $[\text{N II}]$, adopting the median ratio of $f_{[\text{N II}]} / f_{\text{H}\alpha} = 0.33$ found by Kennicutt and Kent (1983) for extragalactic H II regions. To estimate the SFR we adopt the prescription of Kennicutt (1983):

$$\text{SFR} = \frac{L(\text{H}\alpha)}{1.12 \times 10^{41} \text{ erg s}^{-1}} \text{ M}_{\odot} \text{ yr}^{-1}. \quad (7)$$

For $z = 2.313$ the following relations apply, for different values of q_0 :

$$\text{SFR} = 1.76 \times 10^{17} f_{\text{H}\alpha} h^{-2} \text{ M}_{\odot} \text{ yr}^{-1} (q_0 = 0.1), \quad (8)$$

$$\text{SFR} = 8.56 \times 10^{16} f_{\text{H}\alpha} h^{-2} \text{ M}_{\odot} \text{ yr}^{-1} (q_0 = 0.5). \quad (9)$$

Figure 1. Narrow-band ($\lambda = 2.177 \mu\text{m}$, upper) and broad-band (K' , lower) images of the field towards the quasar PHL957. North is up and east is to the left. The central 256×256 ($133 \times 133 \text{ arcsec}^2$) region of each mosaicked frame is shown. The broad-band frame reaches 0.8 mag deeper than the narrow-band frame, but the object C1, a known galaxy at $z = 2.313$, is brighter in the narrow-band frame due to the $\text{H}\alpha + [\text{N II}]$ emission line.

Figure 2. Colour-magnitude diagram for the 30 objects detected in the narrow-band frame at signal-to-noise ratio > 4 . The dot-dashed lines are lines of constant Σ , which is the number of standard deviations of the excess flux in the narrow-band relative to the broad-band, for an object of zero colour $m_{\text{na}} = m_{\text{br}}$. Also shown are lines of constant rest-frame equivalent width, for the redshift of C1, $z = 2.313$. Candidate high-redshift galaxies are objects with equivalent widths $EW_{\text{rf}} > 75 \text{ \AA}$, and $\Sigma > 2$. The line $\Sigma = 2$ corresponds to an SFR of $11h^{-2} M_{\odot} \text{ yr}^{-1}$.

In fact the SFR is proportional to the significance Σ , so the lines of constant Σ in Fig. 2 are lines of constant SFR. The line $\Sigma = 2$ corresponds to an SFR = $22h^{-2} M_{\odot} \text{ yr}^{-1}$ for $q_0 = 0.1$, and to $11h^{-2} M_{\odot} \text{ yr}^{-1}$ for $q_0 = 0.5$.

In addition to C1 there are two other objects that lie above the lines $\Sigma = 2$ and $EW_{\text{rf}} = 75 \text{ \AA}$ (although only just), i.e. their colours are consistent with their being galaxies at the same redshift as C1. The photometry for both objects, in both pass-bands, is consistent from night to night.

5 DISCUSSION

To summarize, we have undertaken a pilot study for a narrow-band H α near-infrared search for high-redshift galaxies. We have imaged a single field with an area of 4.9 arcmin^2 , covering the redshift range $2.29 < z < 2.35$. Applying selection criteria of $EW_{\text{rf}} > 75 \text{ \AA}$, $\text{SFR} > 11h^{-2} M_{\odot} \text{ yr}^{-1}$ there are three objects in the field whose colours are consistent with their being star-forming galaxies at the targeted redshift. One of the objects is a previously known galaxy (C1) of redshift $z = 2.313$, for which we measure an SFR = $18h^{-2} M_{\odot} \text{ yr}^{-1}$. (If C1 harbours an AGN this is an upper limit to the SFR.) This is a factor of only a few times larger than the rate seen in some Sc galaxies today. Our suc-

cessful detection therefore demonstrates the potential of the technique for finding normal galaxies at high redshifts. At a colder site and with a larger telescope, such as UKIRT using the new IRCAM3 instrument, we would reach a limiting flux a factor 2 to 3 fainter with the same integration times.

We can use our measurements of C1 to shed some light on the nature of this object, which is a candidate primeval galaxy. Lowenthal et al. (1991) measure $f_{\text{Ly}\alpha} = (5.6 \pm 0.1) \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}$ and $V = 23.6$ for this galaxy. For a power-law spectral-energy distribution (SED), $f_{\nu} \propto \nu^{\alpha}$, the measured K -band continuum flux density corresponds to $\alpha = 0.1^{+0.6}_{-0.6}$, where the limits are 1σ . Therefore the SED is consistent with the flat SED $\alpha \sim 0$ expected for a young galaxy, but a deeper K' image is needed to place better constraints. The measured H α flux from C1 of $(2.1 \pm 0.6) \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}$ provides confirmation of the tentative spectroscopic detection by Hu et al. (1993) who found $(2.7 \pm 1.2) \times 10^{-16} \text{ erg cm}^{-2} \text{ s}^{-1}$ (where we have corrected their flux estimate for the contribution of [N II]). Therefore we confirm the conclusion of Hu et al. that extinction by dust of the Ly α flux from this galaxy is fairly modest. The ratio $f_{\text{Ly}\alpha}/f_{\text{H}\alpha} = 2.7$ compares with the low-density Case B value of 8.3, and implies a reddening $E(B-V) = 0.16$ (computed using the extinction law of Seaton 1979). This calculation assumes that resonant scattering does not significantly extend the escape path length of the Ly α photons. If, on the other hand, resonant scattering is important, the Ly α line is extinguished selectively relative to the continuum and the true rest-frame Ly α line EW could be substantially larger than the measured value of 140 \AA . If this were the case the object would be classified as an AGN. By measuring the H β line flux the true reddening could be measured, and the intrinsic Ly α line EW inferred.

While the Ly α line in C1 is not greatly affected by dust, this may not be true of most galaxies, given the lack of success of Ly α searches for field galaxies. Therefore the faint flux level reached in the work reported here demonstrates the promise of narrow-band imaging in the near-infrared as a technique for finding normal galaxies at high redshifts. One of the two other possible high-redshift galaxies lies within the field surveyed by Lowenthal et al. (1991) for Ly α emission, but does not show evidence for strong Ly α emission. Infrared spectroscopy of this candidate and others detected in this way will provide a test of the hypothesis that extinction by dust is responsible for the lack of success of surveys for high-redshift galaxies.

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